RADIATION BASICS

1 TYPES OF RADIATION

1.1 Atomic Structure

All matter is composed of chemical elements such as carbon, oxygen, iron, or lead. The smallest "pieces" these elements can be broken into and still retain their identity (i.e., when carbon can still be recognized as carbon) are atoms. All atoms are themselves composed of three basic particles: protons, neutrons, and electrons. The proton carries one positive charge of electricity, the electron carries one negative charge, and the neutron has no charge. The positive protons and neutrons form the densely packed nucleus of the atom. The negative electrons are found in orbit around the nucleus. Each positively-charged proton in the nucleus cancels out a negatively-charged electron, and the atom is electrically neutral. Electrons are much smaller than the protons and neutrons and weigh only 1/1840 as much as a proton. Neutrons and protons are approximately the same weight.

The **atomic weight** of an atom is the total number of neutrons and protons in its nucleus. The **atomic number** refers to the number of protons in the nucleus. In its stable and neutral state, an atom has the same number of electrons as it has protons. It is the number of these charged particles (i.e., protons) that determines the atom's chemical properties. For example, an atom with one proton is a hydrogen atom, and an atom with 92 protons is a uranium atom. The number of neutrons in the nucleus of an atom may vary in number without changing the chemical properties of the atom. A hydrogen atom has one proton (and one electron), but it may, however, have zero, one, or two neutrons. The difference in the number of neutrons changes only the atomic weight, not the atomic number (or the chemical properties of the atom). Therefore, an atom with one proton is hydrogen whether it has one or several neutrons. **Isotopes** are atoms of the same chemical element that have the same number of protons but different numbers of neutrons. Stated another way, all isotopes of a given element have the same atomic number but different atomic weights.

1.2 Radioactivity and Radiation

The nucleus of an atom is normally stable. Some atoms, however, have unstable nuclei due to an imbalance in the ratio of neutrons to protons, and are therefore characterized as being **radioactive**. Similar to isotopes of stable elements, **radioactive isotopes**, or **radionuclides**, are atomic variations of a radioactive element. Two radioactive isotopes of the same element have the same number of protons but different numbers of neutrons. They will also share common chemical properties, but will exhibit different and unique radioactive, and possibly physical, properties because of the differences in their respective nuclear stability and decay modes.

To achieve a stable state, an unstable nucleus of a radioactive atom ejects one or more particles from it nucleus in a process called **radioactive decay** and forms an atom of a different element called a **decay product** or **progeny**. These particles are sometimes accompanied by a release of electromagnetic energy. Together, ejected particles and released energy are called **radiation**. **Radioactivity** may be defined as spontaneous nuclear transformations that result in the formation of new elements. Radioactivity and the radioactive properties of nuclides are determined by nuclear considerations only and are independent of the physical and chemical states of the radioisotope.

There are three principal modes of radioactive decay: alpha, beta, and neutron. **Alpha decay** occurs when the neutron to proton ratio is too low and, as a consequence of this instability, the unstable nucleus ejects an **alpha particle** (alpha radiation). An alpha particle consists of two protons and two neutrons. Emission of an alpha particle from an atom decreases its atomic weight by four and its atomic number by two. Consequently, during alpha decay, one atom of one element changes to an atom of another element. Its chemical properties will also be different from those of its **parent** element and may itself be radioactive. For example, when an atom of ^{226}Ra [1] (with 88 protons and 138 neutrons) emits an alpha particle, it becomes an atom of ^{222}Rn (with 86 protons and 136 neutrons), a gas. Since ^{222}Rn is also radioactive, it will in turn decay to become an atom of still another element until the nucleus becomes stable.

Alpha particles are doubly charged cations, composed of two protons and two neutrons, which are ejected monoenergically from the nucleus of an atom when the neutron to proton ratio is too low. The unit used to describe the energy content of radiation is the **electron volt (eV)—**defined as the energy acquired by any charged particle carrying a unit (electronic) charge when it falls through a potential of 1 volt. This is equivalent to 1.6×10^{-12} ergs. Alpha particles range in energy from 1 to 10 **million electron volts (MeV).** They are physically identical to helium nuclei with positive charges of plus two. Because of their large specific ionization potential, alpha particles expend their energy in short distances. Alpha particles are relatively massive and slow, and will usually not penetrate an ordinary sheet of paper or the outer layer of skin. Consequently, alpha particles represent a significant hazard only when taken into the body where the energy they emit will be completely absorbed by small volumes of tissue.

Beta decay occurs when an electrically-neutral neutron splits into two parts**—**a proton and an electron. The electron is emitted as a **beta particle** (beta radiation) and the proton remains in the nucleus. The atomic number of the resulting decay product is increased by one and the chemical properties of the progeny differ from those of its parent. However, the atomic weight of the decay product remains the same since the total number of neutrons and protons stays the same (a neutron has become a proton, but the total number of neutrons and protons remains the same).

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[1] ^{226}Ra refers to an isotope of radium that contains 88 protons and 138 neutrons and has an atomic weight of 226. Ra is the chemical symbol for radium.

Beta particles are electrons ejected at high speeds from the nucleus of an unstable atom when a neutron spontaneously converts to a proton and an electron. Unlike alpha particles, beta particles are not emitted with discrete energies but are ejected from the nucleus over a continuous energy spectrum with a range of maximum energies between 0.1 and 4 MeV. Because they are smaller than alpha particles and carry a single negative charge, they are less densely ionizing. Unshielded beta sources can constitute external hazards if the beta radiation is within a few centimeters of exposed skin surfaces and if the beta energy is greater than 70 keV, whereas beta sources shielded with certain metallic materials may produce **bremsstrahlung**, or "breaking," (low energy X-ray) radiation which may constitute an external hazard. Internally, beta particles have a much greater range than alpha particles in tissue. However, because of their low specific ionization potential, beta particles will deposit much less energy to small volumes of tissue and consequently will inflict less damage than alpha particles.

Positrons are identical to beta particles except that the charge is positive. Positrons are emitted from the nucleus of neutron-deficient atoms when a proton is spontaneously transformed into a neutron. When an atom decays by positron emission, the atomic number decreases by one, but the mass number remains the same. Alternatively, in cases where positron emission is not energetically possible, the neutron deficiency may be overcome by **electron capture**, whereby one of the orbital electrons is captured by the nucleus and united with a proton to form a neutron.

Neutron decay occurs during nuclear fission reactions, resulting in the emission of a **neutron**, two smaller nuclei, called fission fragments, and beta and gamma radiation. Neutron decay is a very complex subject and unlikely to be encountered or of much concern at most activities addressed by MARSSIM.

Gamma radiation may accompany alpha, beta, or neutron decay. Gamma rays, or photons, belong to the same wave family as light, radio waves, and X-rays. X-rays, which are extra-nuclear in origin, are identical in form to gamma rays, but have slightly lower energies.

Gamma radiation is not particulate radiation, as are the other types of radiation, but is electromagnetic energy emitted from the atomic nucleus. Their energies range from 0.03 to 3 MeV. The emission of a gamma ray does not affect the atomic number or the mass number. There are three main ways in which X- and gamma rays interact with matter:

- photoelectric effect (for energies <1 MeV)
- Compton effect (important for energies between 200 keV and 5 MeV)
- pair production (which requires energies ≥1.02 MeV).

All three processes yield electrons which then ionize or excite other atoms of the substance. Because of their high penetration ability, X- and gamma radiations are of most concern as external hazards.

In summary, the larger a particle is and the larger the electrical charge it has, the less it will penetrate through matter. Alpha particles are relatively massive and carry a double positive charge. Their ability to penetrate matter is therefore limited. Beta particles will penetrate farther than alpha particles because they have less mass and only carry a single negative charge. Gamma radiation has no mass or charge and will therefore be highly penetrating radiation. As a relative indication of penetrating power, an alpha particle can be stopped by a sheet of paper, beta radiation can be stopped by a sheet of aluminum, and gamma radiation can be stopped by dense material such as concrete or lead. Examples of alpha, beta and gamma emitters are given in Figure 4 at the end of this attachment.

1.3 Ionization

Normally, an atom is electrically neutral because the number of electrons exactly equals the number of protons. **Ionization** of an atom is the removal of one of its orbital electrons. When an electron is removed, two charged particles, or ions, result: the free electron, which is electrically negative, and the rest of the atom, which bears a net positive charge. These are called an **ion pair**.

Radiation is one mechanism that produces ionization. Alpha and beta radiation cause ionization primarily through collisions (i.e., moving alpha and beta particles physically "collide" with orbital electrons, transferring some or all of their energy to these electrons). Numerous collisions with electrons eventually reduce the energy of the alpha or beta particle to zero. The particle is then absorbed or stopped. De-energized beta particles become free electrons, which are often absorbed by positive ions. A doubly-positive alpha particle frequently captures two free electrons to become a helium atom. Gamma radiation causes ionization by three processes: the photoelectric effect, the Compton effect, and pair production. The first process is the **photoelectric effect** in which the total energy of the gamma photon (or ray) is absorbed by an electron and the incident gamma photon in annihilated. The second process is the **Compton effect** in which a part of the energy of the gamma photon is transferred to an orbital electron and the initial incident gamma photon is deflected with reduced energy. In the third process, **pair production**, the incident gamma photon interacts with the atomic nucleus forming two electrons. The incident gamma photon is annihilated.

Alpha, beta, and gamma radiation are referred to as **ionizing radiation** because of their ability to remove orbital electrons from neutral atoms. The number of ion pairs produced depends on the mass and charge of the incident radiation. Because of their relatively massive size and charge, alpha particles create more ion pairs than do beta particles, which in turn create more ion pairs than do gamma photons. Since it may take more than one ionizing collision to absorb a radiation particle or a photon, a particle or a photon may produce several ion pairs. **Total ionization** is the total number of ion pairs produced by radiation, whereas **specific ionization** is the number of ion pairs produced per unit path length (for instance, 1 inch). Since the larger particles have a better chance of colliding with neutral atoms, they will collide with more atoms in a given distance and have a higher specific ionization.

2 UNITS OF MEASURE

Quantities of radioactive isotopes are typically expressed in terms of activity at a given time t. The International System (SI) unit of activity is the **becquerel (Bq)**, which is defined as the quantity of a given radioisotope in which one atom is transformed per second (i.e., one disintegration per second or 1 dps). The conventional unit of activity is the **curie (Ci)**, defined as the quantity of a given radioisotope that undergoes nuclear transformation or decay at a rate of 3.7 x 10^{10} (37 billion) disintegrations each second. One Ci is equal to 3.7 x 10^{10} Bq and approximately equal to the decay rate of one gram of ^{226}Ra. Because the curie is a very large amount of activity, subunits of the curie are often used:

1 millicurie (mCi)	=	10^{-3} Ci
1 microcurie (μCi)	=	10^{-6} Ci
1 nanocurie (nci)	=	10^{-9} Ci
1 picocurie (pCi)	=	10^{-12} Ci
1 femtocurie (fci)	=	10^{-15} Ci

As mentioned above, **disintegrations per minute (dpm)** is a unit that describes the average number of radioactive atoms in a source disintegrating each minute. A 500 dpm source, for example, will have 500 atoms disintegrating every minute on the average. **Counts per minute (cpm)** is the number of disintegrations <u>detected</u> by a radiation-detection instrument. Because radiation is emitted isotropically (i.e., equally in all directions) from a radioactive source, the probes of most radiation-detection instruments cannot detect all the radiations emitted from a source. Therefore, cpm and dpm will not be equal. However, if the response characteristics of a detector are known for a given radiation source, the relationship between cpm and dpm can be determined. This relationship, defined as the ratio of the number of disintegrations detected by a radiation instrument per minute (cpm) to the number of disintegrations taking place by the radioactive source per minute (dpm), is known as the **counting efficiency** of the detecting instrument. For example, if a source is 1,600 dpm and the instrument is detecting 400 cpm, the counting efficiency of this detection system is 0.25 (400/1,600 = 1/4) or 25%.

3 HALF-LIFE AND DECAY LAW

As defined previously, radioactivity is the spontaneous transformation or decay of one atom of an element resulting in the formation of another atom of a different element. Each radioactive isotope has its own unique rate of decay which cannot be altered by physical or chemical operations. One measure of the speed with which a radioisotope undergoes transformation is its **radioactive half-life** (sometimes referred to as the physical half-life). Radioactive half-life, $\mathbf{t_{1/2}}$, is the time required for any given radioisotope to decrease to one-half its original quantity. For example, if one starts with 1,000 atoms of ^{131}I which has half-life of 8 days, the number of atoms of ^{131}I remaining after 8 days (one half-life), 16 days (two half-lives), and 24 days (three half-lives) will be 500, 250, and 125, respectively. In fact, the fraction of the initial quantity of any radioisotope remaining after n half-lives can be represented by the following relationship:

$$\frac{A}{A_0} = \frac{1}{2^n} \qquad \textbf{(1)}$$

where A_0 is the initial activity and A is the activity left after n half-lives. After one half-life (n=1), 0.5 (or 50%) of the initial activity remains; after three half-lives (n=3), 13% remains; and after five half-lives (n=5), 3% remains. Further, the activity of any radioisotope is reduced to less than 1% after 7 half-lives. For radioisotopes with half-lives greater than six days, the change in activity in 24 hours will be less than 10%. Over 1,600 different radioisotopes have been identified to date, with half-lives ranging from fractions of a second to billions of years (half-lives for many radionuclides are listed as part of Figures 1 to 4 at the end of this appendix.

The **activity** of a radioactive isotope is defined as the average number of nuclear disintegrations that occur per unit time. Activity is the product of the number of atoms and the **radioactive**

$$A = -\lambda N \qquad \textbf{(2)}$$

decay constant, λ, of a given radioisotope, and can be defined as follows:
where A is the activity of the radioisotope in units of disintegration per second (dps) or disintegrations per minute (dpm), N is the number of atoms present at a specified time, and λ is the decay constant in reciprocal units of time (i.e., sec^{-1} or min^{-1}), defined as:

$$\lambda = \frac{\ln(2)}{t_{1/2}} \approx \frac{0.693}{t_{1/2}} \qquad \textbf{(3)}$$

As a result of the radioactive decay process, one element is transformed into another. The newly-formed element, the decay product or progeny, may itself be radioactive and eventually decay to form another element. Moreover, this second decay product may be unstable and in turn decay to form a third, fourth, fifth or more generation of other radioactive decay products. This serial decay relationship is know as a **radioactive decay chain** or **decay series**. A decay series begins with a **parent radioisotope** (also called a parent radionuclide or parent nuclide) which decays to form one or more progeny. The final decay product in the series will be a stable element or an element with an extremely long half-life. Examples of important naturally occurring decay series include the uranium series, the thorium series, and actinium series (see Figures 1, 2 and 3).

There are three important reasons for identifying a decay series and to characterize the properties of each decay product in each series:

- First, the total activity content (and the potential hazard) of a radioactive source may be substantially underestimated if the activity contributions from each decay product are not included. If one incorrectly assumes that only one **radionuclide of potential concern** is present in a source, when in fact one or more decay products may also be present, then the total activity of and threat posed by that source will not be accurately assessed.
- Second, decay products may be much more toxic, either alone or in combination, than the parent nuclide. Because each radioactive isotope possesses its own unique chemical, physical, and radioactive properties, the hazard presented by decay products may be substantially greater than that posed by the parent nuclide.
- Third, the environmental fate, transport, and bioaccumulation characteristics of the decay products may be completely different from those of the parent nuclide.

In a decay chain, an unstable atom of one radioisotope (the parent isotope) decays and forms a new atom of another element which in turn decays to form a new atom of another element, and so forth, until a stable or very long-lived atom is formed. At that point, the decay chain ends or is stopped. This relationship between atoms of series members can be illustrated as follows:

$$\mathbf{N_1 \quad N_2 \quad N_3 \qquad N_n\ (stable)}$$

where N_1 is the number of atoms of the parent radioisotope decaying to form atoms of the first decay product, N_2, which in turn decays to form atoms of the second decay product, N_3, which continues to decay until a stable atom, N_n is formed.

Some example decay chains include the uranium, actinium, and thorium series. The uranium series (Figure 1) can be divided into several subseries with the first one consisting of ^{238}U, ^{234}Th, ^{234}Pa, and ^{234}U. The long radioactive half-life of ^{234}U (2.5E+5 years) allows time for isotopic fractionation from alpha-emission recoil of ^{234}Th and chemical processes in the rest of the chain. ^{234}U is removed from soils at a greater rate than ^{238}U and builds up in greater activity concentrations in the oceans. The second uranium subseries, headed by ^{234}U, includes ^{230}Th and ^{226}Ra. The third subseries, headed by ^{226}Ra, consists of ^{222}Rn, a noble gas, and its short half-life progeny, ^{218}Po, ^{214}Pb, ^{214}Bi, and ^{214}Po. Another subseries consists of the longer-lived radon decay products, ^{210}Pb, ^{210}Bi, and ^{210}Po, and terminates with the formation of stable ^{206}Pb.

The actinium series (Figure 2) also shows radionuclides with half-lives long enough to cause disequilbriumm, however, this is not readily broken into subseries. The thorium series (Figure 3) consists of long-lived ^{232}Th and its relatively short-lived progeny. Given no migration of progeny, the series reaches equilibrium in 60 years. In minerals and rocks of low permeability, the thorium series is expected to be in equilibrium. In soils, waters, natural gas, petroleum, and the atmosphere, the chemical and physical properties of the progeny can cause disequilibrium.

4 TYPES OF RADIONUCLIDES

Radionuclides present in the natural environment can be divided into three groups according to origin:

(1) **Naturally occurring series and non-series radionuclides** include those radionuclides of primordial origin and terrestrial nature, which possess sufficiently long half-lives to have survived in detectable quantities since the formation of the earth (about 3 billion years ago),and their radioactive decay products.

(2) **Cosmogenic radionuclides** are those radionuclides continually produced by natural cosmic processes in the atmosphere other than the decay of naturally occurring series radionuclides.

(3) **Ubiquitous manmade radionuclides** are radionuclides generated by man's activities and are widely-distributed in the environment.

The naturally occurring radionuclides include the several dozen or more radionuclides of the uranium, thorium, and actinium series, which decay through a series of other radionuclides (i.e., the series isotopes) to eventually form isotopes of stable lead, as well as a group of radionuclides which decay straight to a stable isotope (i.e., the so called non-series radioisotopes).

The radioisotopes ^{238}U, ^{235}U, and ^{232}Th head the uranium (Figure 1), actinium (Figure 2), and thorium series (Figure 3), respectively. When the decay members of these series are not subjected to either chemical or physical separation processes, a state of secular equilibrium is obtained wherein the progeny decay at the same rate as the nuclide which heads the series. Each series can be further divided into several subseries on the basis of differences in the radioactive and physical properties of the progeny. These differences provide decay members with the means of separating from each other and their immediate precursors in the environment. Figure 4 lists radionuclides of potential concern in the environment along with some of their characteristics. Releases of radionuclides produced by nuclear fission—in boiling water reactors (BWRs) and in pressurized water reactors (PWRs)—occur because of periodic fuel failure, defects, or corrosion that result in transfer of some fission and activation products into the reactor coolant.

5 TYPES OF EQUILIBRIUM

There are three types of activity equilibrium that can be established between decay series members: secular, transient, and no equilibrium. **Secular equilibrium** refers to the state of equilibrium that exists when series radioisotopes have equal and constant activity levels. This equilibrium condition is established when the half-life of the parent isotope is much greater than that of its decay product(s) (i.e., $t_{1/2}$ of the parent >>> $t_{1/2}$ of the decay product, or when expressed in decay constants, $\lambda_2 >> \lambda_1$). **Transient equilibrium** is the state of equilibrium existing when the half-life of the parent isotope is slightly greater than that of its decay product(s)

(i.e., $t_{1/2}$ of the parent > $t_{1/2}$ of the decay product, or $\lambda_2 > \lambda_1$) and the decay product activity surpasses that of the parent. **No equilibrium** is the state that exists when the half-life of the parent isotope is smaller than that of the decay product(s) (i.e., $\lambda_2 < \lambda_1$). In this latter case, the parent activity will decay quickly, leaving only the activity of the decay product(s).
To illustrate the state of secular equilibrium, consider the activity levels of ^{237}Np (half-life, 2 million years) and its immediate decay product ^{233}Pa (27 days). Suppose the initial activity of ^{237}Np (alone) at time t=0 is 100 Bq, and the initial activity of ^{233}Pa is 0 Bq. The activity of ^{237}Np at any time t can be calculated, and the activity of ^{233}Pa can be calculated at the same time points, as shown in Table 1.

Table 1 Example of Secular Equilibrium: ^{237}Np/^{233}Pa

Time (days)	Activity of ^{237}Np (Bq)	Activity of ^{233}Pa (Bq)	Np + Pa (Bq)
0	100	0	100
15	100	32	132
30	100	54	154
90	100	90	190
150	100	98	198
300	100	100	200
3,000	100	100	200
2 million years	50	50	100

As shown in Table 1, the activity of ^{233}Pa increases (builds up) over time as a function of its half-life: After 10 half-lives (approximately 300 days), the activity level of ^{233}Pa equals that of ^{237}Np, and the source activity (^{237}Np plus ^{233}Pa) is twice its initial level. At this point in time (and at all subsequent times), ^{233}Pa is said to be in a state of secular equilibrium (i.e., equal activity level) with its parent isotope, ^{237}Np.

To illustrate the state of transient equilibrium, consider the activity levels of ^{212}Pb (half-life, 11 hours) and its immediate decay product ^{212}Bi (61 minutes). Suppose the initial activity of ^{212}Pb (only) at time t=0 is 1,000 Bq, and the initial activity of ^{212}Bi is 0 Bq. The activities of ^{212}Pb, ^{212}Bi, and the source (^{212}Pb + ^{212}Bi) can be calculated as shown Table 2.

Table 2 Example of Transient Equilibrium: $^{212}Pb/^{212}Bi$

Time (hours)	Activity of ^{212}Pb (Bq)	Activity of ^{212}Bi (Bq)	Pb + Bi (Bq)
0	1,000	0	1,000
1	939	479	1,418
3.8	781	781	1,562
10	533	576	1,109
20	284	301	585
50	39	43	82
75	8	8	16

As shown in Table 2, the activity of ^{212}Bi builds up rapidly as ^{212}Pb decays: After 3.8 hours, the activity level of ^{212}Bi equals that of ^{212}Pb, and the source activity (Pb plus Bi) is 56% greater than its initial level. At this point in time (and for all subsequent times), ^{212}Bi activity surpasses that of ^{212}Pb by a constant fraction of 1.1 (or 10% greater activity) and a state of transient equilibrium exists.

In the case where the half-life of the decay product exceeds that of the parent, no equilibrium is possible. Consider the activity levels of ^{210}Bi (half-life, 5 days) and its immediate decay product ^{210}Po (138 days). Suppose the initial activity of ^{210}Bi (only) at time t=0 is 1,000 Bq, and the initial activity of ^{210}Po is 0 Bq. The activities of ^{210}Bi, ^{210}Po, and the source (^{210}Bi + ^{210}Po) can be calculated as shown in Table 3.

As shown in Table 3, the activity of ^{210}Po reaches a maximum at 25 days and then reaches a point where it decays at its own rate (after approximately 7 parent half-lives or 35 days). The parent, because of its shorter half-life, decays away. The total activity of the source does not reach a maximum; it decreases continuously.

Because of the complexities involved in determining the activities of decay chain members, the following rules of thumb are given to provide approximations of these activity values:

(1) A conservative approach is to assume that all decay products in a series are present and are in secular equilibrium with the parent nuclide. (However, note that this assumption may be overly conservative if one of the decay members possesses a half-life longer than the time period of interest (see Rule 3).)

Table 3 Example of No Equilibrium: $^{210}Bi/^{210}Po$

Time (days)	Activity of ^{210}Bi (Bq)	Activity of ^{210}Po (Bq)	Bi + Po (Bq)
0	1,000	0	1,000
5	500	18	518
25	31	32	63
30	16	32	48
40	4	31	35
50	1	29	30
100	<0.01	23	23
200	<<0.01	14	14

(2) If the half-life of a series member is less than one-third to one-half the time period of interest (e.g., the time since burial in the ground), then the series members activity can be approximated as being equal to that of the parent (i.e., in secular equilibrium). After two half-lives, approximately 75 percent of the decay product has grown in; after three half-lives, approximately 85 percent has grown in.

(3) Rule 2 applies to all decay products down to the first member with a half-life equal to or twice as long as the time period of interest. Such a relatively long-lived decay product effectively "stops" the decay chain. This radioisotope and subsequent radioactive members in the series may be neglected without appreciable error. (Note that this rule should not be applied to radioisotopes belonging to the naturally occurring uranium and thorium decay chains—unless one can demonstrate that these radioisotopes, or any of the preceding members of the series, have been physically separated from all other series members.)

(4) If the parent nuclide has a half-life equal to one-seventh the time period of interest, one can assume that less than one percent of the activity of the parent remains and the activity of the first decay product will be $A_d = A_p(t/_{1/2p}/t_{1/2d})$, where $t_{1/2p}$ is the half-life of the parent (p) and $t_{1/2d}$ is the half-life of the first decay product (d). Subsequent series members will behave according to rules 2 and 3 (and to this rule, if their half-lives are also short compared to the time period of interest).

6 INTERACTION OF RADIATION WITH MATTER

Several terms are used to define the quantity or amount of radiation energy (or dose) transferred to and absorbed by different media, such as air or biological material. **Exposure** (sometimes called the exposure dose) refers to the number of ionizations occurring in a unit mass of air due to the transfer of energy from a gamma or X radiation field emitted by a radioactive source. The unit of exposure is the **roentgen (R)** expressed as coulombs of charge per kilogram of air (1 R = 2.5×10^{-4} C/kg). **Exposure rate** (or exposure dose rate) refers to the amount of gamma or X radiation, in R, transferred to air per unit time (e.g., R/hr or R/yr). Commonly used subunits of the roentgen are the milliroentgen (mR) and the microroentgen (μR), with corresponding subunits of mR/hr or μR/hr for exposure rates. The roentgen may be used to measure gamma or X radiation only.

The **absorbed dose (D)** is defined as the mean energy imparted by ionizing radiation per unit mass of material (e.g., biological tissue). The SI unit of absorbed dose is the joule per kilogram, also assigned the special name the **gray** (1 Gy = 1 joule/kg). The conventional unit of absorbed dose is the **rad** (1 rad = 100 ergs per gram = 0.01 Gy). The **dose equivalent (H)** takes into account the unequal biological effects produced from equal absorbed doses of different types of radiation, and is defined as:

$$\mathbf{H = DQN}$$

where D is the absorbed dose, Q is the quality factor that takes into account different biological effects, and N is the product of any modifying factors. Quality factors currently assigned by the International Commission on Radiological Protection (ICRP) include Q values of 20 for alpha particles, 10 for neutrons and protons, and 1 for beta particles, gamma photons and X rays. These factors may be interpreted as follows: on the average, an alpha particle will inflict approximately 20 times more damage to biological tissue than a beta particle or gamma ray, and twice as much as a neutron. The modifying factor is currently assigned a value of unity (N=1) for all radiations. The SI unit of the dose equivalent is the **sievert** (Sv) and the conventional unit is the **rem** (1 rem = 0.01 Sv). A commonly used subunit of the rem is the millirem (mrem).

A rule of thumb is that an exposure of 1 R of gamma or X radiation in air will be approximately equal to 1 rad of absorbed radiation dose in tissue, and also be approximately equal to 1 rem of radiation dose equivalent (i.e., for gamma and X radiation, 1 R   1 rad   1 rem). This rule can be applied to exposure and dose rates; in other words, 1 R/hr   1 rad/hr   1 rem/hr.

Internal doses to specific human tissues and organs are typically reported in terms of the **committed dose equivalent ($H_{T,50}$)**, which is defined as the integral of the dose equivalent in a particular tissue for 50 years after intake (corresponding to a working lifetime). The **effective dose equivalent (H_E)** and the **committed effective dose equivalent ($H_{E,50}$)**, defined as the weighted sums of the organ-specific dose equivalents, were developed by the ICRP to account for different cancer induction rates and to normalize radiation doses and effects on a whole body basis for regulation of occupational exposure.

Working level (WL) is a special unit used to describe exposure to the short-lived radioactive decay products of radon (^{222}Rn) and is defined as any combination of radon decay products in one liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy. The **working level month (WLM)** is defined as the exposure to 1 WL for 170 hours (1 working month).

Although the becquerel is a measure of the activity of a radioactive source, it does not provide information about the number of atoms or atomic mass of the radioactive material. This information can be obtained, however, if the atomic weight and the mass of the emitter are known. The number of becquerels per gram (or curies per gram) of radioactive material, or the **specific activity (SpA)**, can be calculated by the following equations:

$$SpA\ (Bq/g) = \frac{4.8\ x\ 10^{18}}{(half\text{-}life,\ days)(atomic\ weight)} \quad \textbf{(4)}$$

$$SpA\ (Ci/g) = \frac{1.3\ x\ 10^{8}}{(half\text{-}life,\ days)\ (atomic\ weight)} \quad \textbf{(5)}$$

For example, the SpA for the long-lived, naturally occurring uranium isotope ^{238}U (half-life, 4.51×10^9 years) is 3.3×10^{-7} Ci/g, whereas the SpA for the short-lived phosphorous isotope ^{32}P (half-life, 14.3 days) is 2.9×10^5 Ci/g. Expressed in another way, one curie of ^{238}U would weigh 3.0 megagrams (10^6 grams or about 6,600 lbs), whereas one curie of ^{32}P would weigh 3.4 micrograms (10^{-6} gram). From this example it is clear that the shorter the half-life (i.e., the faster disintegration rate) of radioisotope, the smaller the amount of material will be required to equal a curie quantity; conversely, the longer the half-life of a radioisotope, the larger the amount of material will be required to obtain a curie amount. The specific activity of a radioisotope is one of the major factors determining its relative hazard.

7 ACRONYMS AND DEFINITIONS

7.1 Acronyms and Abbreviations

A(t)	=	Activity at time t
Bq	=	Becquerel
C	=	Coulomb
Ci	=	Curie
cpm	=	counts per minute
D	=	absorbed dose
dpm	=	disintegrations per minute
dps	=	disintegrations per second

eV	=	electron volt
Gy	=	Gray
H	=	dose equivalent
H_E	=	effective dose equivalent
$H_{E,50}$	=	committed effective dose equivalent
$H_{T,50}$	=	committed dose equivalent
ICRP	=	International Commission on Radiological Protection
λ	=	radioactive decay constant
MeV	=	Million electron volts
μCi	=	microCurie (10^{-6} Ci)
N	=	modifying factor in the definition of dose equivalent
	=	number of atoms present at a specified time
pCi	=	picoCurie (10^{-12} Ci)
Q	=	Quality factor in definition of dose equivalent
R	=	Roentgen
SI	=	International System of Units
SpA	=	specific activity
Sv	=	Sievert
T	=	tissue or target organs
$t_{1/2}$	=	radioactive half-life
WL	=	working level
WLM	=	working level month

7.2 Definitions

absorbed dose (D): The mean energy imparted by ionizing radiation to matter per unit mass. The special SI unit of absorbed dose is the gray (Gy); the conventional unit is the rad (1 rad = 0.01 Gy).

activity: The average number of nuclear disintegrations that occur per unit time.

alpha ( ) decay: One of the three principal modes of radioactive decay. When the neutron to proton ratio is too low the unstable nucleus ejects an alpha particle.

alpha ( ) particle: Doubly charged cations composed of two protons and two neutrons which are ejected monoenergetically from an unstable nucleus as a result of radioactive decay.

atomic number: The number of protons in the nucleus of an atom.

atomic weight: The total number of protons and neutrons in the nucleus of an atom.

Becquerel (Bq): One nuclear disintegration per second; the name for the SI unit of activity. 1 Bq = 2.7 x 10^{-11} Ci.

beta ( ) decay: One of the three principal modes of radioactive decay. When an electrically-neutral neutron splits into two parts (a proton and an electron) and the electron is emitted from the nucleus. The atomic number of the decay product is increased by one and the chemical properties differ from those of the parent.

beta ( ) particle: An electron emitted at high speed from the nucleus of an unstable atom when a neutron spontaneously converts to a proton and an electron. Beta particles are not emitted with discrete energies but are ejected from the nucleus over a continuous energy spectrum.

committed dose equivalent ($H_{T,50}$): The total dose equivalent (averaged over tissue T) deposited over the 50-year period following the intake of a radionuclide.

committed effective dose equivalent ($H_{E,50}$): The weighted sum of committed dose equivalent to specified organs and tissues, in analogy to the effective dose equivalent.

Compton effect: A process by which gamma and X radiation interacts with matter when a part of the energy of the photon is transferred to an orbital electron and the initial incident photon is deflected with reduced energy.

counting efficiency: The ratio of the number of disintegrations detected by a radiation instrument (counts) to the number of disintegrations taking place by the radioactive source.

Curie (Ci): 3.7×10^{10} nuclear disintegrations per second, the name for the conventional unit of activity. 1 Ci = 3.7×10^{10} Bq.

decay chain, decay series: A serial decay relationship where a parent radionuclide decays to one or more radioactive progeny, which in turn decay to form a third, fourth, or more generation of radioactive progeny. The final decay product in the series will be a stable element or an element with an extremely long half-life.

decay product(s): A radionuclide or a series of radionuclides formed by the nuclear transformation of another radionuclide which, in this context, is referred to as the parent.

dose equivalent (H): The product of the absorbed dose (D), the quality factor (Q), and any other modifying factors (N). The SI unit of dose equivalent is the Sievert (Sv); the conventional unit is the rem (1 rem = 0.01 Sv).

electron capture: A form of radioactive decay in neutron-deficient atoms whereby one of the orbital electrons is captured by the nucleus and united with a proton to form a neutron.

electron volt (eV): The energy acquired by any charged particle carrying a unit (electronic) charge when it falls through a potential of 1 volt. 1 eV = 1.6×10^{-12} ergs.

effective dose equivalent (H_E): The sum over specified tissues of the products of the dose equivalent in a tissue or organ (T) and the weighting factor for that tissue, wT, i.e., $H_E = T\ w_T\ H_T$.

exposure: The number of ionizations occurring in a unit mass of air due to the transfer of energy from a gamma or X radiation field emitted by a radioactive source.

exposure (internal): The situation leading to intake of a radionuclide including the situation existing after a radionuclide has been deposited in an organ or tissue.

exposure (external): The situation leading to irradiation of the body from external radiation.

exposure rate: The amount of gamma or X radiation (in R) transferred to air per unit time.

gamma ( ) radiation: Photons of energy originating from the nucleaus that may accompany alpha, beta, or neutron decay. Gamma radiation is <u>not</u> a mode of radioactive decay.

Gray (Gy): The special name for the SI unit of absorbed dose. 1 Gy = 1 Joule kg^{-1} = 100 rad.

ionizing radiation: Any radiation capable of displacing electrons from atoms thereby producing ions.

ionization: The removal of an orbital electron from an atom.

isotope: Atoms of the same chemical element that have the same number of protons but different numbers of neutrons. Atoms with the same atomic number but different atomic weights.

neutron decay: One of the three principal modes of radioactive decay. The emission of a neutron, two smaller nuclei (fission fragments), and beta and gamma radiation that occurs during nuclear fission reactions.

no equilibrium: The state of equilibrium when the half-life of the parent is smaller than that of the decay products.

pair production: A process by which gamma and X radiation interacts with matter where the incident photon interacts with the atomic nucleus forming two electrons and annihilating the incident photon.

parent radionuclide: A radioactive atom that undergoes radioactive decay and forms another, different radionuclide.

photoelectric effect: A process by which gamma and X radiation interact with matter where the total energy of the photon is absorbed by an electron and the incident photon is annihilated.

positron ($^{+}$): A positively-charged beta particle.

Quality factor (Q): The principal modifying factor that is employed in deriving dose equivalent, H, from absorbed dose, D; chosen to account for the relative biological effectiveness (RBE) of the radiation in question. Q is independent of the tissue or organ under consideration, and of the biological endpoint. For radiation protection purposes, the quality factor is determined by the linear energy transfer (LET) of the radiation.

rad: The name for the conventional unit for absorbed dose of ionizing radiation; the corresponding SI unit is the gray (Gy); 1 rad = 0.01 Gy = 0.01 Joule/kg.

radiation: The ejected particles and released energy emitted from an atom as a result of radioactive decay.

radioactive: Atoms with unstable nuclei due to an imbalance in the ratio of neutrons to protons.

radioactive decay: The process by which the unstable nucleus of a radioactive atom ejects one or more particles to achieve a more stable state.

radioactive half-life ($t_{1/2}$): The time required for any given radioisotope to decrease to one-half its original quantity.

radioactivity: Spontaneous nuclear transformations that result in the formation of new elements.

radioisotope, radionuclide: A radioactive species of atom characterized by the number of protons and neutrons in its nucleus.

rem: An acronym of radiation equivalent man, the name for the conventional unit of dose equivalent; the corresponding SI unit is the Sievert; 1 Sv = 100 rem.

roentgen (R): The unit of exposure expressed as coulombs of charge per kilogram of air (1 R = 2.5×10^{-4} C/kg).

secular equilibrium: The state of equilibrium that exists when series radioisotopes have equal and constant activity levels. Secular equilibrium is established when the half-life of the parent is much greater than that of the decay products.

Sievert (Sv): The special name for the SI unit of dose equivalent. 1 Sv = 100 rem = 1 Joule per kilogram.

transient equilibrium: The state of equilibrium that occurs when the half-life of the parent is slightly greater than that of the decay products and the decay product activity surpasses that of the parent.

Working Level (WL): Any combination of short-lived radon decay products in 1 liter of air that will result in the ultimate emission of 1.3×10^5 MeV of alpha energy.

Working Level Month (WLM): A unit of exposure corresponding to a concentration of radon decay products of 1 WL for 170 working hours (1 work month).

X radiation: Photons of energy originating from the electron shells of an atom.

Figure 1. Uranium Decay Series[*]

Radioisotope (atomic #)	**Historical name**	**Half-life[**]**	**Major radiation energies (MeV) and intensities[***]**		
U-238 (92)	Uranium I	4.51 x 10^9 y	4.15 (25%) 4.20 (75%)	---	---
Th-234 (90)	Uranium X_1	24.1 d	---	0.103 (21%) 0.193 (79%)	0.063c (4%) 0.093c (4%)
Pa-234m† (91)	Uranium X_2	1.17 m	---	2.29 (98%)	0.765 (0.3%) 1.001 (0.6%)
U-234 (92)	Uranium II	2.47 x 10^5 y	4.72 (28%) 4.77 (72%)	---	0.53 (0.2%)
Th-230 (90)	Ionium	8.0 x 10^4 y	4.62 (24%) 4.68 (76%)	---	0.068 (0.6%) 0.142 (0.07%)
Ra-226 (88)	Radium	1602 y	4.60 (6%) 4.78 (95%)	___	0.186 (4%)
Rn-222 (86)	Radon (gas)	3.82 d	5.49 (100%)	---	0.510 (0.07%)
Po-218† (84)	Radium A	3.05 m	6.00 (~100%)	0.33 (~0.02%)	---
Pb-214 (82)	Radium B	26.8 m	---	0.65 (50%) 0.71 (40%) 0.98 (6%)	0.295 (19%) 0.352 (36%)
Bi-214† (83)	Radium C	19.7 m	5.45 (0.012%) 5.51 (0.008%)	1.0 (23%) 1.51 (40%) 3.26 (19%)	0.609 (47%) 1.120 (17%) 1.764 (17%)
Po-214 (84)	Radium C′	164 µs	7.69 (100%)	---	0.799 (0.014%)
Pb-210 (82)	Radium D	21 y	---	0.016 (85%) 0.061 (15%)	0.047 (4%)
Bi-210 (83)	Radium E	5.01 d	4.65 (0.00007%) 4.69 (0.00005%)	1.161 (~100%)	---
Po-210 (84)	Radium F	138.4 d	5.305 (100%)	---	0.803 (0.0011%)
Pb-206 (82)	Radium G	Stable	---	---	---

[*] Source: Lederer and Shirley (1978) and Shleien and Terpilak (1984).
[**] Half-life given in seconds (s), minutes (m), days (d), or years (y).
[***] Intensities refer to percentage of disintegrations of the nuclide itself, not to the parent of the series.
† Approximately 0.13% of all Pa-234m particle emissions form an intermediate radioisotope, Pa-234 (6.75 hrs: -emitter), before decaying to U-234. For Po-218, 0.02% decays through At-218 (~2 sec: -emitter) before forming Bi-214. For Bi-214, 0.02% decays through Tl-210 (1.3 m: -emitter) to Pb-210.

Figure 2. Actinium Decay Series*

Radioisotope (atomic #)	Historical name	Half-life**	Major radiation energies (MeV) and intensities***		
U-235 (92)	Actinouranium	7.1 x 10^8 y	4.37 (18%) 4.40 (57%) 4.58c (8%)	---	0.143 (11%) 0.185 (54%) 0.204 (5%)
Th-231 (90)	Uranium Y	25.5 h	---	0.140 (45%) 0.220 (15%) 0.305 (40%)	0.026 (2%) 0.084c (10%)
Pa-231 (91)	Protactinium	3.25 x 10^4 y	4.95 (22%) 5.01 (24%) 5.02 (23%)	---	0.027 (6%) 0.29c (6%)
Ac-227† (89)	Actinium	21.6 y	4.86c (0.18%) 4.95 (1.2%)	0.043 (~99%)	0.70 (0.08%)
Th-227 (90)	Radioactinium	18.2 d	5.76 (21%) 5.98 (24%) 6.04 (23%)	---	0.050 (8%) 0.237c (15%) 0.31c (8%)
Ra-223 (88)	Actinium X	11.43 d	5.61 (26%) 5.71 (54%) 5.75 (9%)	___	0.149c (10%) 0.270 (13%) 0.33c (6%)
Rn-219 (86)	Actinon (gas)	4.0 s	6.42 (8%) 6.55 (11%) 6.82 (81%)	---	0.272 (9%) 0.401 (5%)
Po-214† (84)	Actinium A	1.78 ms	7.38 (~100%)	0.74 (~0.0002%)	---
Pb-211 (82)	Actinium B	36.1 m	---	0.29 (1.4%) 0.56 (9.4%) 1.39 (87.5%)	0.405 (3.4%) 0.427 (1.8%) 0.832 (3.4%)
Bi-211† (83)	Actimium C	2.15 m	6.28 (16%) 6.62 (84%)	0.60 (0.28%)	0.351 (14%)
Tl-207 (81)	Actinium C´´	4.79 m	---	1.44 (99.8%)	0.897 (0.16%)
Pb-207 (82)	Actinium D	Stable	---	---	---

* Source: Lederer and Shirley (1978) and Shleien and Terpilak (1984).
** Half-life given in seconds (s), minutes (m), days (d), or years (y).
*** Intensities refer to percentage of disintegrations of the nuclide itself, not to the parent of the series.
† Approximately 1.4% of all Ac-227 emissions form an intermediate radioisotope, Fr-223 (22 m: -emitter), before decaying to Ra-223. For Po-215, 0.00023% decays through At-215 (~ 0.1 msec: -emitter), before forming Bi-211. For Bi-211, 0.28% decays through Po-211 (0.52 sec: -emitter) to Pb-207.

Figure 3. Thorium Decay Series*

Radioisotope (atomic #)	Historical name	Half-life**	Major radiation energies (MeV) and intensities***		
Th-232 (90)	Thorium	1.41×10^{10} y	3.95 (24%) 4.20 (75%)	---	---
Ra-228 (88)	Mesothorium I	6.7 y	---	0.005 (100%)	---
Ac-228 (89)	Mesothorium II	6.13 h	---	1.18 (35%) 1.75 (12%) 2.09 (12%)	0.34c (15%) 0.908 (25%) 0.96c (20%)
Th-228 (90)	Radiothorium	1.910 y	5.34 (28%) 5.43 (71%)	---	0.084 (1.6%) 0.214 (0.3%)
Ra-224 (88)	Thorium X	3.64 d	5.45 (6%) 5.68 (94%)	---	0.241 (3.7%)
Rn-220 (86)	Thoron (gas)	55 s	6.29 (100%)	___	0.55 (0.07%)
Po-216 (84)	Thorium A	0.15 s	6.78 (100%)	---	---
Pb-212 (82)	Thorium B	10.64 h	---	0.346 (81%) 0.586 (14%)	0.239 (47%) 0.300 (3.2%)
Bi-212† (83) (64%) (36%)	Thorium C	60.6 m	6.05 (25%) 6.09 (10%)	1.55 (5%) 2.26 (55%) 0.98 (6%)	0.040 (2%) 0.727 (7%) 1.620 (1.8%)
Po-212 (84)	Thorium C	304 ns	8.78 (100%)	---	---
Tl-208 (81)	Thorium C´	3.01 m	---	1.28 (25%) 1.52 (21%) 1.80 (50%)	0.511 (23%) 0.583 (86%) 0.860 (12%) 2.614 (100%)
Pb-208 (82)	Thorium D	Stable	---	---	---

* Source: Lederer and Shirley (1978) and Shleien and Terpilak (1984).
** Half-life given in seconds (s), minutes (m), hours (h), days (d), or years (y).
*** Intensities refer to percentage of disintegrations of the nuclide itself, not to the parent of the series.
† Percentages in brackets are branching fractions.

Figure 4. Radiological Characteristics of Selected Radionuclides *

		Principal Particulate and Photon Energies in MeV (% Abundance)		
Nuclide	Half-life**	Alpha	Beta (max)	Gamma
Am-241	4.32E+02 y	5.49 (85%), 5.44 (13%), 5.3	---	X-rays, 0.060 (36%)
Am-243	7.38E+03 y	5.28 (88%), 5.23 (11%)	---	X-rays, 0.075 (66%), 0.044 (6%)
Ba-137m	2.55E+00 h	---	---	0.662 (85%)
C-14	5.73E+02 y	---	0.156	---
Ce-144	2.84E+02 d	---	0.310	X-rays, 0.080 (2%), 0.134 (11%)
Cm-243	2.85E+01 y	5.79 (73%), 5.74 (11%), 6.06 (5%)	---	X-rays, 0.209 (4%), 0.228 (12%), 0.278 (14%)
Cm-244	1.81E+01 y	5.81 (76%), 5.76 (24%)	---	X-rays, 0.043 (0.02%)
Co-60	5.27E+00 y	---	0.318	1.173 (100%), 1.332 (100%)
Cr-51	2.77E+01 d	---	EC	X-rays, 0.320 (10%)
Cs-134	2.06E+00 y	---	0.662	0.57 (23%), 0.61 (98%), 0.80 (99%), 1.365 (3%)
Cs-135	2.30E+06 y	---	0.205	---
Cs-137	3.00E+01 y	---	0.514	---
Fe-59	4.45E+01 d	---	0.475	---
H-3	1.23E+01 y	---	0.019	---
I-129	1.57E+07 y	---	0.152	X-rays, 0.040 (8%)
I-131	8.04E+00 d	---	0.606	X-rays, 0.28 (6%), 0.36 (81%), 0.64 (7%), 0.72 (2%)
K-40	1.28E+09 y	---	1.312	X-rays, 1.46 (11%)
Mn-54	3.12E+02 d	---	EC	X-rays, 0.835 (100%)
Mo-99	6.60E+01 h	---	1.23	X-rays, 0.04 (1%), 0.18 (6%), 0.74 (13%), 0.78 (4%)
Nb-94	2.03E+04 y	---	0.471	0.703 (100%), 0.871 (100%)
Np-237	2.14E+06 y	4.80 (47%), 4.77 (25%), 4.64 (6%)	---	X-rays, 0.03 (14%), 0.086 (13%), 0.143 (1%)
P-32	1.43E+01 d	---	1.710	---
Pb-210	2.23E+01 y	---	0.061	X-rays, 0.047 (4%)
Po-210	1.38E+02 d	5.305 (100%)	---	
Pu-238	8.77E+01 y	5.50 (72%), 5.46 (28%)	---	X-rays
Pu-239	2.41E+04 y	5.16 (74%), 5.11 (11%), 5.14 (15%)	---	trace gamma
Pu-240	6.54E+03 y	5.17 (73%), 5.12 (26%)	---	X-rays, trace gamma
Pu-241	1.44E+01 y	trace	0.021	X-rays, trace gamma
Pu-242	3.76E+05 y	4.90 (78%), 4.86 (22%)	---	X-rays

Figure 4 (Cont.)

Nuclide	Half-life**	Principal Particulate and Photon Energies in MeV (% Abundance) Alpha	Beta (max)	Gamma
Ra-226	1.60E+03 y	4.78 (94%), 4.60 (6%)	---	X-rays, 0.186 (3%)
Ra-228	5.75E+00 y	---	0.04	---
Ru-106	3.68E+02 d	---	0.039	---
S-35	8.74E+01 d	---	0.167	---
Sr-89	5.05E+01 d	---	1.491	0.91 (trace)
Sr-90	2.91E+01 y	---	0.546	---
Tc-99	2.13E+05 y	---	0.293	---
Tc-99m	6.02E+00 h	---	IT	X-rays, 0.141 (89%)
Th-230	7.70E+04 y	4.69 (76%), 4.62 (23%)	---	X-ray, 0.07 (0.4%)
Th-232	1.41E+10 y	4.01 (77%), 3.95 (23%)	---	X-rays, 0.06 (0.2%)
U-234	2.44E+05 y	4.77 (72%), 4.72 (27%)	---	X-rays, others (trace)
U-235	7.04E+08 y	4.60 (5%), 4.40 (56%), 4.37 (18%)	---	X-rays, 0.144 (11%), 0.184 (54%), 0.205 (5%)
U-238	4.47E+09 y	4.20 (77%), 4.15 (23%)	---	X-rays

*Source: ICRP 1983, Kocher 1981.
**Half-time expressed in years (y), days (d) and hours (h). Note some half-life data are different from Figures 1, 2 and 3.